Geotechnical Engineering in the XXI Century: Lessons learned and future challenges
N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190041

Impact of Salinity Level in Pore Fluid on the Compressibility of Champlain Sea Clay

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Abstract. This paper presents an experimental investigation of leaching on the compressibility of sensitive Champlain Sea clay. Champlain Sea clay is prominent in eastern Canada, commonly found in the St. Lawrence River Valley. It has an open fabric structure formed during its deposition in sea water and tends to have a very high compressibility. A leaching apparatus was developed to flush fresh water through a 15 cm undisturbed clay sample and reduce the salinity from 19.81 g/L of pore fluid to 0.79 g/L in 83 days. A total of four constant rate of strain consolidation tests were conducted on unleached and leached clay samples. Based on the consolidation test results, a few minor changes were observed in the corresponding samples, including an increased sensitivity, a higher compression index, a reduced permeability, and a reduced coefficient of consolidation due to leaching. However, there are no significant differences in compressibility properties of Champlain Sea clay at these two salinity levels.

Keywords. Salinity, compressibility, champlain sea clay, leaching, CRS consolidation test.

1. Introduction

The eastern part of Canada was overrun by an arm of Champlain Sea about 8,000-12,000 years ago [1]. When the ice melted, sediments were deposited from detritus of streams, erosion of shorelines, and ice melting. These deposits are now known as Champlain Sea clay or Leda clay. It is commonly found along the St. Lawrence Lowlands regions in Ontario and Quebec [2]. The most well-known feature of Champlain Sea clay is its transformation from a relatively brittle material to liquid when it is disturbed [3]. Destruction of the fabric of clay may be due to induced stress or remolding of the clay. The weak particle bonds and high water content are the reasons behind its change state to fluid [4].

Like other sensitive marine clays, Champlain Sea clay has an open fabric structure formed during its deposition in seawater and tends to have a very high compressibility. Structures built on top of it can experience excess settlement over the decades [1]. Due to its marine deposit nature, Champlain Sea clay also has a high salinity level in its pore fluid. For example, the salinity level of clay samples in this study varies from 10 to 26 g/L compared to the salinity level of 35 g/L in sea water [5].

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Leaching of salinity in the pore fluid can have a profound impact on the geotechnical properties of sensitive marine clay. Many researchers have investigated the impact of leaching on the geotechnical properties of marine clays through a series of leaching and consolidation experiments. For example, tests were conducted to investigate the impact of leaching on the physical properties of Norwegian clay and it was found that Norwegian clay was transformed into quick clay when the soil salinity was reduced to very low values [6, 7, 8]. In Norway, the salt-leaching theory seemed to be a key reason behind sensitivity of clay. However, according to Torrance [9], the reduced salinities is one of the requirements for the development of high sensitivity of the marine clays, the existence of low salinity pore water does not guarantee that high sensitivity will be observed. There are many other factors that influence on the sensitivity of clay [10, 11].

2. Compressibility of Champlain Sea Clay

Sensitive clays normally exhibit a unique *e-log p* curve, which can be divided into three distinctive zones: 1) Zone one from start to its pre-consolidation pressure, σ_p; Zone two from σ_p to transition stress σ_t; Zone three beyond σ_t [12]. Most clays exhibit only Zone one and Zero three, while Zone two is associated with the cementation bonds failure found in sensitive clay [13].

A decrease in the soil salinity leads to an increase in soil compressibility [9, 14]. The compression index, swelling index, and settlement tend to increase due to leaching. Brand & Brenner [15] reported that leaching could reduce shear strength and increase the compressibility of the clay. An investigation conducted by Bjerrum [16] on the samples showed an increase in compressibility when a reduction of pore fluid salt concentration from 21 g/L to 1 g/L. A series of consolidation tests were performed by Torrance [9] to investigate the effect of leaching on the consolidation behavior of remoulded and undisturbed Norwegian clay. Leaching process was achieved by diffusion process with distilled water. The results of his experiments illustrate that the quasi-preconsolidation pressure of the samples reduces due to leaching. Because of a reduction in σ_p, leached clay was observed to experience a spontaneous settlement. Recently, Song et al. [17] investigated the effect of pore fluid salinity on the consolidation of reconstituted marine clay using an oedometer. They found salt leaching increases the compressibility of the illite-dominant reconstructed marine clays and the change is attributed to the decrease in the void ratio at the liquid limit.

In this study, a total of four constant rate of strain (CRS) consolidation tests were conducted on undisturbed clay samples at two salinity levels. A test apparatus was developed to leach a 15 cm diameter undisturbed clay sample for various geotechnical tests and investigate the impact of leaching on its compressibility.

3. Test Program and Testing Devices

3.1. Leaching Apparatus Designed for the Study

A leaching apparatus was developed in this study, which consists of a distilled water reservoir, a pump to fill the system, a pressure tank, pressure gauges to regulate the pressures in the system, and a leaching mould modified from a 15 cm permeability cell to host the sample. The details of its components are shown in Figure 1.

The leaching apparatus was developed to prepare a large size leached sample for accommodating more tests on the same sample, including index properties, compressibility, and shear strength. In addition, the leaching conditions can be better controlled in this set-up and avoid prolonged time to leach a small sample in an expensive testing apparatus, like a triaxial system by Moore et al. [14] and a CRS machine by Kim and Do [18].

A clay cutting device was also developed to precisely trim and insert a Champlain Sea clay sample into the 15 cm diameter 12 cm high leaching mould or the 5 cm diameter 2.54 cm high CRS ring. The device is adjustable to trim clay samples with a size varying from 2 to 40 cm.

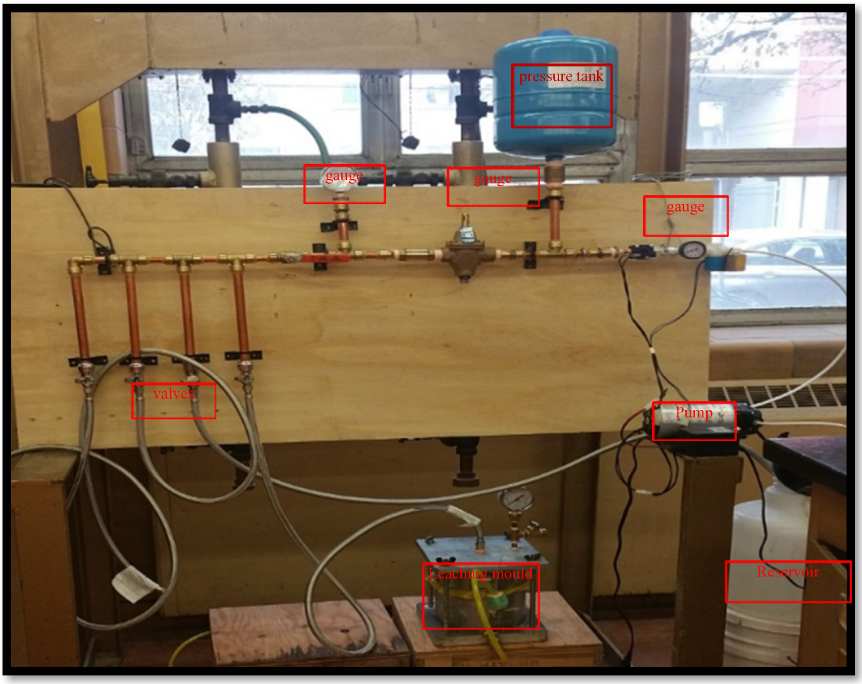


Figure 1. Developed apparatus for leaching samples under constant head conditions.

3.2. Sample Preparation Procedures

A series of undisturbed 20 cm diameter and 22 cm high Champlain Sea clay samples were retrieved with a Laval sampler from a dam site in the town of Arnprior, approximately 65 km to the west of Ottawa [5]. One of Laval samples was used in this study.

First, the Laval clay sample was inserted carefully into the leaching mould. The surface of the clay sample was first smoothened by a wire saw. The diameter was trimmed off about 2 cm with a scraper. The sample pushed slowly at an increment of approximately 5 mm into the leaching mould. This procedure was repeated until 120 mm of the clay sample was inserted into the mould and then a filter paper and a pore stone were placed on either side of the sample inside the mould. The water flow was one-dimensional, which is similar to the method used by McCallister and Petry [19] in their flexible wall leaching tests.

Second, distilled de-aired water was pumped into the system from a reservoir. Then the water pressure was adjusted through a pressure regulator to a desired value. A pressure of 100 kPa was selected in this study to be lower than the preconsolidation pressure of clay sample and also high enough to generate a constant seepage through the low permeability clay sample.

Third, the mould was connected to the leaching apparatus and distilled water was flowed constantly through the sample and leachate was collected continuously and measured for both volume and salinity. For the samples used in this study, a leaching time of 83 days was used before the sample was taken out of mould for testing.

Last, the sample was extruded from the leaching mould for various tests, including index properties, vane shear strength, and CRS consolidation tests.

3.3. CRS test apparatus and Test Procedures

The CRS test has grown increasingly popular in recent decades for consolidation testing on sensitive clays. This is in part due to its ability to capture a very large number of data points with which to better define the consolidation curve. The CRS testing machine used in this experiment is an automated consolidation system manufactured by GeoTac.

Distilled water was used to fill the CRS cell for two leached samples while the collected leachate was used for two unleached samples. This was to minimize any effect of diffusion during the CRS tests.

A back pressure of 350 kPa was applied for 24 hours to saturate the specimen before the start of consolidation. The strain rates of 1%/hr for loading and 0.25%/hr for unloading were used for Sample 1 (Leached) and Sample 2 (Unleached) and a loading rate of 0.8%/hr and an unloading rate of 0.2%/hr were used for Sample 3 (Leached) and Sample 4 (Unleached). These strain rates were selected to keep the pore water pressure to mean effective stress ratio within the range of the recommended value of 3-15% as per ASTM D4186 and also similar to rates applied by other researchers [20]. The different loading rates were intended to see any impact of loading rate and found not big enough to generate any appreciate differences in the compressibility curves.

4. Test Results and Discussions

4.1. Pore-Fluid Salinity

The salinity of clay sample was measured by the diluted fluid method. For obtaining the salinity level of clay sample, a small block of clay sample was first oven dried. Then a known mass of dried clay was dissolved into a known volume of distilled water, and the salinity level was recorded using Horiba ES-5 portable conductivity/salinity meter. The initial salinity of soil was recorded 19.81 g/L of salt per liter of pore water (equivalent to 12.68 g/kg of salt mass to dry soil mass). After 83-day leaching, the salinity in clay sample was reduced to 0.79 g/L (0.505 g/kg).

The leachate collected from the tests was recorded and measured at an interval of one to two days. A total of 8032 ml of leachate associated with 11.93 g of salt was collected from the sample in the 83-day leaching process. The leaching of salt in clay can be divided into two stages: Stage one with a drastic drop in the salinity level due to displacing of original pore fluid by fresh water; Stage two with a slower reduction over time due to leaching of salts by diffusion from the double-layer around the clay particles.

At the end of the leaching process, the uniformity of salinity level inside the sample was confirmed by similar salinity levels measured at three different locations inside the sample.

4.1.1. Change of Sensitivity Due to Leaching

The sensitivity of clay was determined by dividing the undrained shear strength, s_u, of an undisturbed sample by that of a remoulded sample. The mini vane shear tests were conducted to obtain s_u of both samples according to ASTM D4648.

s_u of the leached sample were significantly lowered than those of the unleached sample under both undisturbed and disturbed conditions. Due to leaching, s_u of the undisturbed sample was reduced significantly from 91.5 kPa for the unleached condition to 21.59 kPa for leached condition. At the same time, s_u of the remoulded sample was also reduced from 22.6 kPa to only 2.45 kPa. Correspondingly, the sensitivity of Champlain Sea clay was increased from 4.1 under the salinity level of 19.81 g/L to 8.8 for salinity level of 0.79 g/L. This sensitivity increase is similar to one reported by other researchers [6].

4.1.2. Change of Compressibility Indices Due to Leaching

A total of four (4) CRS tests were performed on undisturbed leached (UL) and undisturbed unleached (UU) samples to evaluate the effect of leaching on Champlain Sea clay.

The *e-log p* curves for all four samples are shown in Figure 2. First of all, these compression curves resemble the typical compression curves of sensitive clay with a prominent cementation bonds failure zone immediately after σ_p. Second, it is very difficult to notice any significant impact of two different salinity levels, though the compression index, *Cc*, in leached samples was observed higher than unleached samples, shown in Table 1. The higher Cc values in UL samples suggest that the cementation bonds failure became more abrupt due to leaching. There was almost no void ratio change due to leaching, ranging from 1.97 to 2.01 for all four samples. This is similar to the similar void ratios reported by Hong et al. [21]. The sudden drop in the void ratio reported by Torrance [9] was not observed in this study.

Third, there is no significant change in σ_p ranging from 300 to 320 kPa for all four samples. This small variation can be considered due to the testing errors and sample disturbances. There are many methods available to identify σ_p of sensitive clays. The graphic method proposed by Nagaraj et al. [12] was used in this study due to its simplicity.

Last, no significant changes in the compressibility curves of the samples further indicate that the strain rate difference between samples was not large enough to generate any appreciate impact on the compressibility of undisturbed samples.

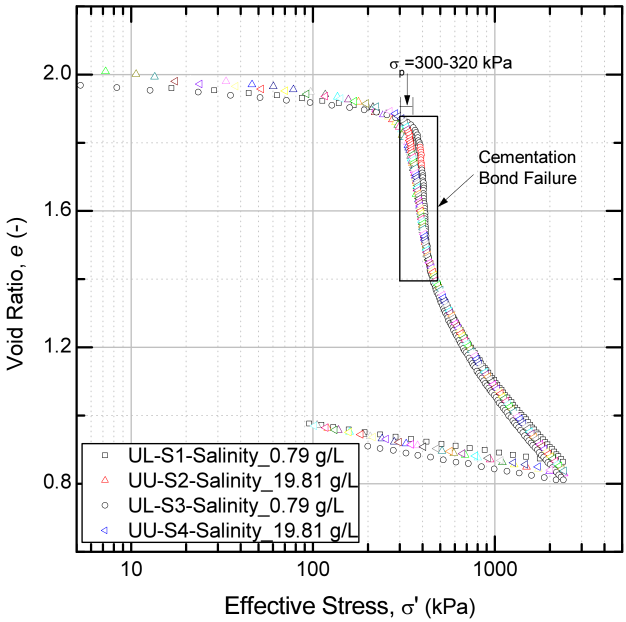


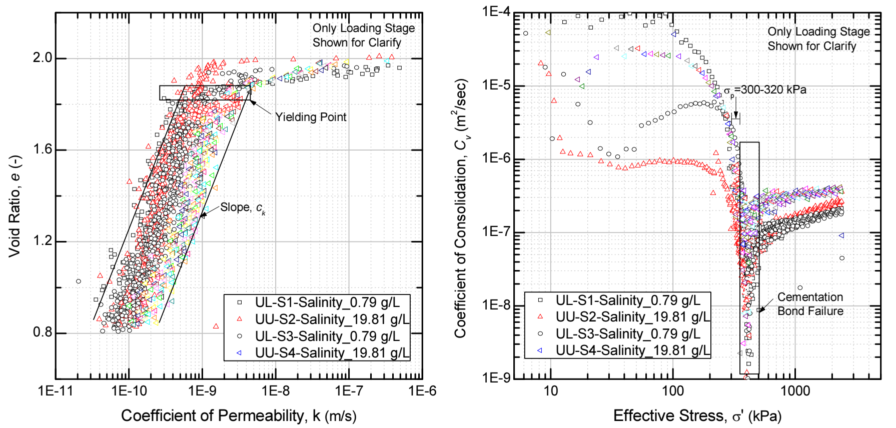
Figure 2. Influence of leaching on e-log p curve of undisturbed Sample.

4.1.3. Change of Permeability Due to Leaching

The change of coefficient of permeability, k, with stress is shown in Figure 3a where only the loading stage is shown for clarity. It is a bi-linear change of k with stress in a semi-log scale figure. It can be seen that the permeability was decreased with a decrease of the void ratio induced by a stress increase. The change of k can be divided into two phases: Phase one, k sharply reduces with an increase of stress from 4E-6 m/s to around 1 E-9 m/s in its over consolidation state. After σ_p, k reduces at a much slower pace from around 1E-9 m/s at the void ratio around 1.8 at σ_p to 1E-10 m/s at the void ratio of 0.9 corresponding to the vertical stress around 2 MPa. The slope of k change with stress, c_k are shown in Table 1 for different samples. In general, the leached samples tend to have slightly lower k than corresponding unleached samples. However, no significant changes were observed in the test results. More tests are needed to confirm this finding.

4.1.4. Change of Consolidation Coefficient Due to Leaching

The change of coefficient of consolidation, C_v, is plotted against the vertical stress in Figure 3b. C_v reduces gradually with an increase in stress in the over-consolidated state. When the stress passed σ_p, there was a sudden drop in Cv due to the cementation bonds failure where a significant change in the volume occurred at that zone with a minimal stress increase. In Zone three, Cv actually increases gradually with an increase in stress. Unleached samples tend to have a lower Cv than that of corresponding unleached samples in Zone one while a higher Cv in Zone two and Zone three. In general, the fluctuation of Cv values can be higher than a few orders of magnitude during the process of compression.



a) Permeability b) coefficient of consolidation

Figure 3. Influence of leaching on the permeability and consolidation coefficient of Champlain Sea clay.

The summary of consolidation properties of all samples is shown in Table 1, where some of compression properties are presented at three stages of tests: initial condition measured around the vertical stress of 10 kPa, end of over-consolidation stage measured at σ_p, and the maximum vertical stress around 2MPa.

Table 1. List of compression parameters of leached and unleached Champlain Sea clay samples.

Spec.No.	Sal. (g/L)	σ_p (kPa)	*Cc-II* (-)	*Cc-III* (-)	*Cr* (-)	Initial		Stress at σ_p			Stress at 2 MPa		
						e (-)	*k* ($\times10^{-7}$ m/s)	*e* (-)	*k* ($\times10^{-10}$m/s)	*Cv* ($\times10^{-9}$ m²/s)	e (-)	k ($\times10^{-10}$m/s)	*Cv* ($\times10^{-9}$m²/s)
1	0.79	310	3.10	0.69	0.08	1.91	10	1.79	9	2	0.81	0.7	200
2	19.81	300	2.32	0.73	0.10	2.01	2	1.8	10	70	0.81	0.7	300
3	0.79	320	3.61	0.73	0.10	1.94	2	1.8	10	1	0.80	0.7	200
4	19.81	310	2.64	0.74	0.10	1.99	2	1.8	20	100	0.83	2	400

Sal-Salinity level, σ_p-preconsolidation pressure, $C_{c\text{-II}}$- compression index at zone two, $C_{c\text{-III}}$- compression index at zone three, Cr- swelling index, e- void ratio, *k*-coefficient of permeability, *Cv*-coefficient of consolidation

5. Conclusions

A total of four CRS consolidation tests were conducted to investigate the impact of leaching on the compressibility behavior of sensitive Champlain Sea clay. A leaching apparatus was developed to seep distilled water to reduce the salinity of a 15 cm diameter undisturbed Champlain Sea clay sample from 19.81 g/L of pore fluid to 0.79 g/L. Based on these CRS test results, the following conclusions can be drawn:

There are no significant changes in the density and void ratio of the sample due to leaching at the current salinity levels.

No significant change can be found in preconsolidation pressure of the samples. However, an increase in the compression index was observed in cementation bond failure zone due to leaching.

More tests with a wider range of salinity levels are needed to obtain a full picture of the leaching impact on the geotechnical properties of Champlain Sea clay, including compressibility characteristics and shear strength.

Acknowledgments

This study was made possible with funding from the National Sciences and Engineering Research Council of Canada and Keller Canada Inc. through a Collaborative & Research & Development Grant entitled by “Deep mixing to stabilize Champlain Sea clay.” The authors would also like to acknowledge the use of undisturbed Laval samples collected by Ontario Power Generation for its Dam Safety Program.

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